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**A Distributed Active Vibration Absorber (DAVA) and Associated  
Control Approaches for Active-Passive Reduction of Sound and  
Vibration**

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January 4, 2001

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Develop and demonstrate a prototype distributed active vibration absorber (DAVA) which is lightweight, conformal and cost effective. To develop and demonstrate a bio hierarchical controller approach for high actuators/sensor count system. To develop and demonstrate associated design procedures. To initiate transition of the technology to applications in AF launch vehicles payloads, USN Next Generation Torpedoes and NASA Aircraft Interior Noise Programs.

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## Program Objectives

The program objectives were:

1. Develop and demonstrate a prototype distributed active vibration absorber (DAVA) which is lightweight, conformal and cost effective.
2. To develop and demonstrate a bio hierarchical controller approach for high actuators/sensor count system.
3. To develop and demonstrate associated design procedures.
4. To initiate transition of the technology to applications in AF launch vehicles payloads, USN Next Generation Torpedoes and NASA Aircraft Interior Noise Programs

Figure 1 presents a project timetable for the research work. The approach in general is to investigate the system (i.e. launch vehicle, torpedo etc) noise mechanisms, design DAVA's using numerical and experimental data, apply to the system and measure the results. For the BIO controller we have initially developed a novel controller arrangement based upon system physics, built and an analytical model to efficiently investigate its behavior and then experimentally implemented the controller. Experimental tests have been performed initially on laboratory structures and then on real system structures such as payload fairings and aircraft fuselages. The work performed and results obtained in the two main areas of Distributed Vibration Absorbers (DAVA) and BIO controllers is described below. It should be noted that years two and three were not supported so the project goals of year 1 were only completed. Thus only the achievements of year 1 are summarized below.

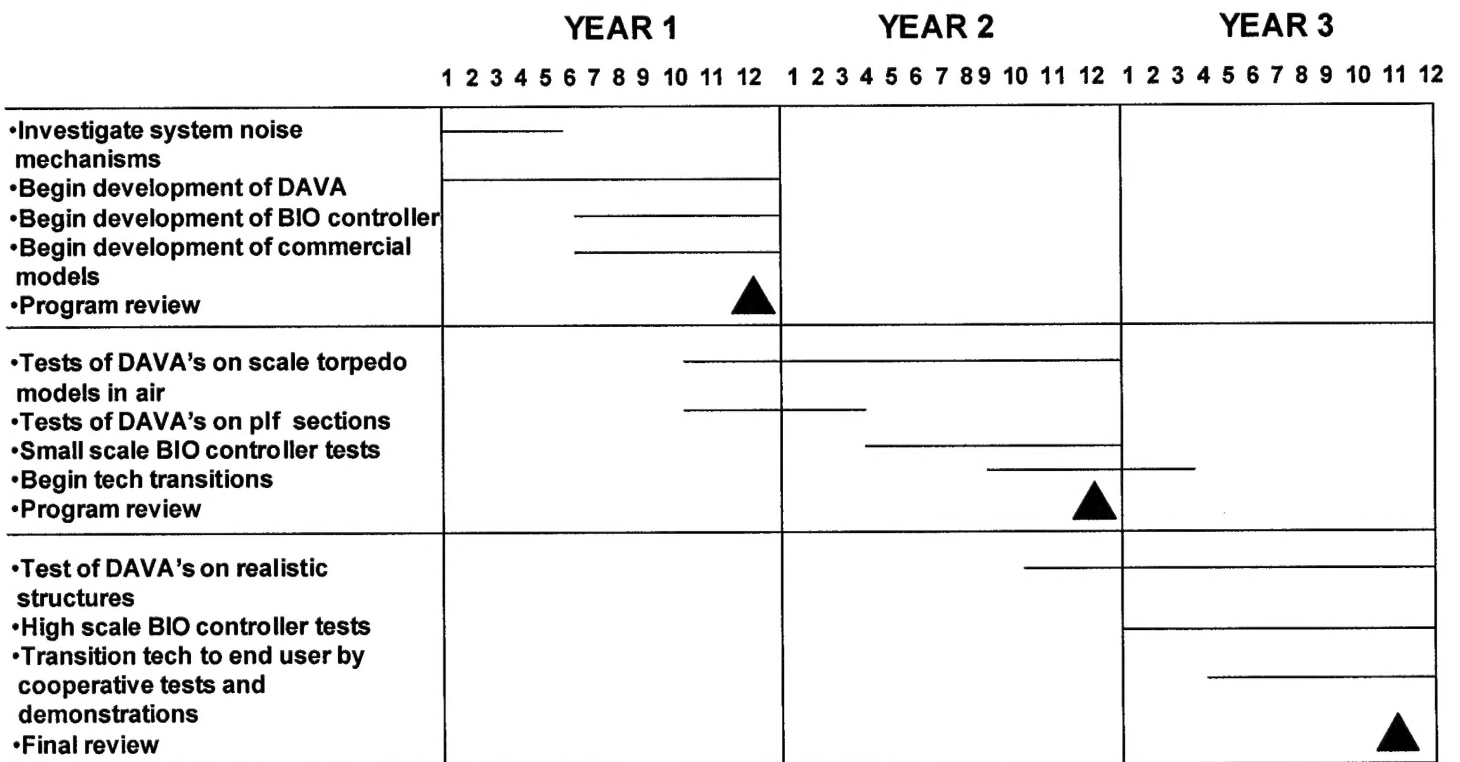


Figure 1. Project timeline

## ***Research on Distributed Active Vibration Absorbers (DAVA)***

Figure 2 shows a schematic of a Distributed Vibration Absorbers (DAVA). Essentially a DAVA consists of a point TVA whose mass and spring is spread over an extended area of the structure. The mass spring layer applies a distributed reactive force to the structure and thus controls vibration over an extended area instead of at a point. At higher frequencies the top mass remains stationary while the base structure displaces normally. This leads to normal “squeeze” damping and enhanced damping characteristics at very low frequencies. The DAVA forms a conformal lightweight layer that is readily integrated into the structural surface. Active inputs allow for control forces to be applied to the structure outside the effective bandwidth of the passive mechanism of the DAVA.

In this year of work an analytical model of the DAVA was developed using a Rayleigh-Ritz variational formulation, and used to investigate and understand its behavior as well as optimally design it for various applications [1]. Our discussion here is limited to application of DAVA's to control of vibration and sound radiation from torpedo like structures in air. Figure 3 shows a schematic of a typical DAVA developed for this application with a bandwidth of 0 to 800Hz. The distributed spring is realized using thin acoustic foam while active inputs are provided by embedded segments of PVDF. The active mass is constructed from a thin lead sheet. The DAVA is 1.3cm thick and weighs 7% of the structure to be controlled. Design was achieved using the analytical model.

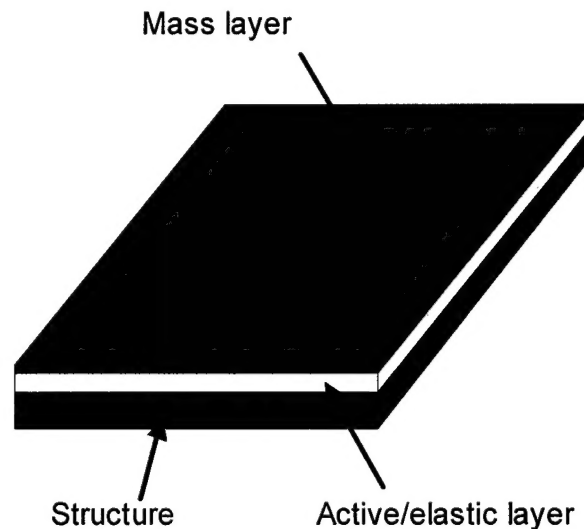


Figure 2. Schematic of DAVA arrangement

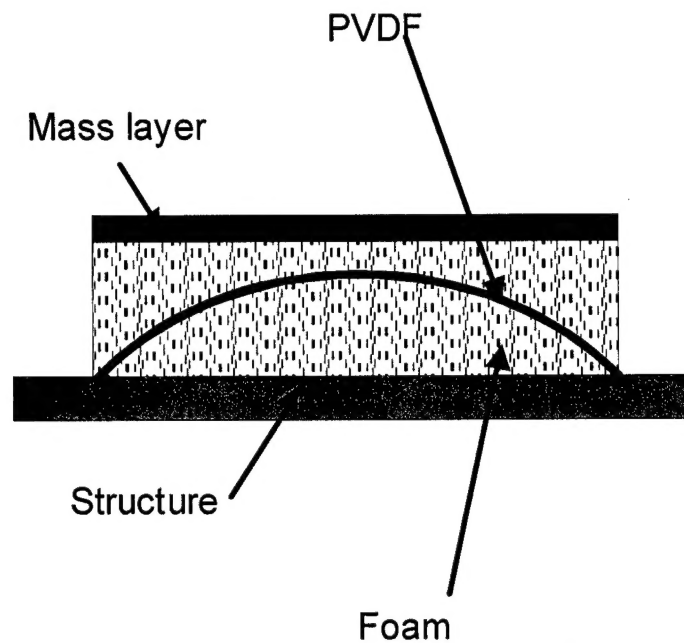


Figure 3. DAVA for torpedo cylinder radiation control

Figure 4 is a photo of the experimental rig consisting of a scale torpedo cylinder in air, excited by a broadband vibration input of bandwidth 0 to 800Hz. Three DAVA's are located on the exterior of the cylinder for convenience. These could easily be located on the interior. Large visco-elastic constrained layer patches are bonded to the cylinder to represent in-water radiation damping. Control is applied using a MIMO digital feedforward controller.

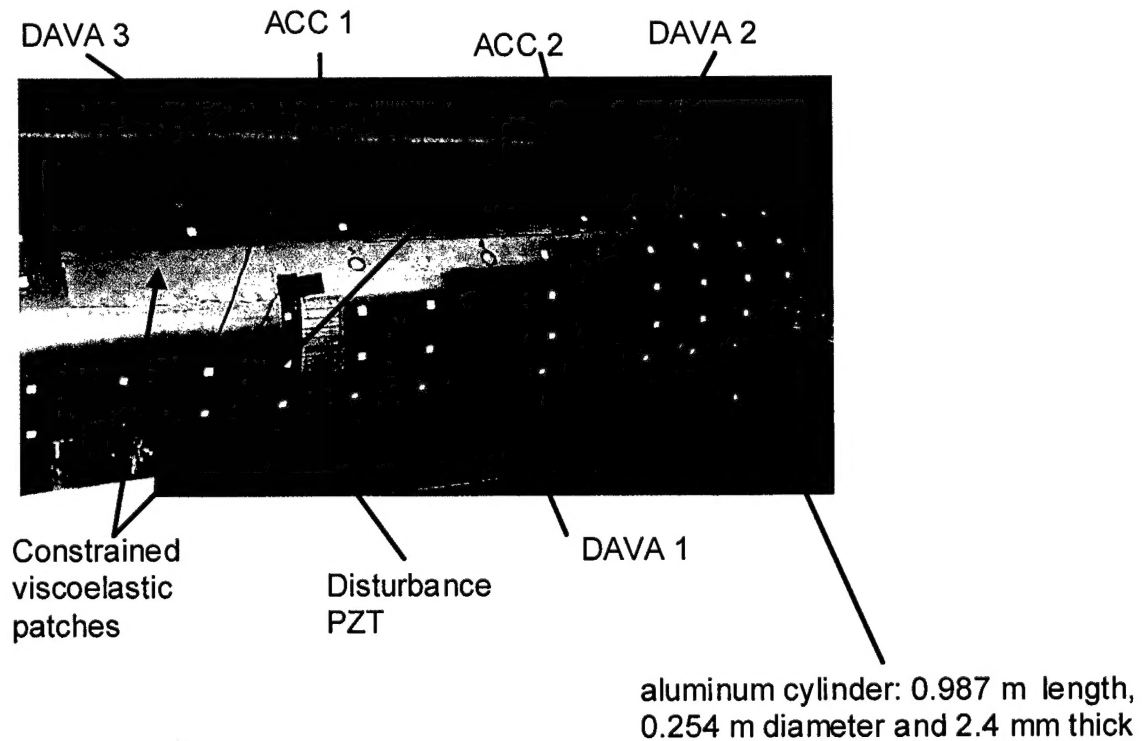


Figure 4. DAVA experimental rig

Figure 5 presents an illustrative result of attenuation of the global vibration of the cylinder monitored with an array of accelerometers under various conditions. For the bare cylinder, the response is dominated by damped peaks at the resonant frequencies of various modes of the cylinder. When the DAVA's are glued to the cylinder wall but with no active control, large attenuations are evident near the DAVA design frequency of 275 Hz. This is due to the distributed reactive forces of the DAVA's. Notice that the DAVA's also provide excellent damping at the modal resonance's and this is due to the "squeeze" damping effect discussed above. When the active is turned on, there is a significant reduction in the global vibration over the control bandwidth of 200 to 800Hz and the total active/passive attenuation across the band is 26.3dB. Measurements indicate a corresponding reduction in radiated sound power of 18dB.

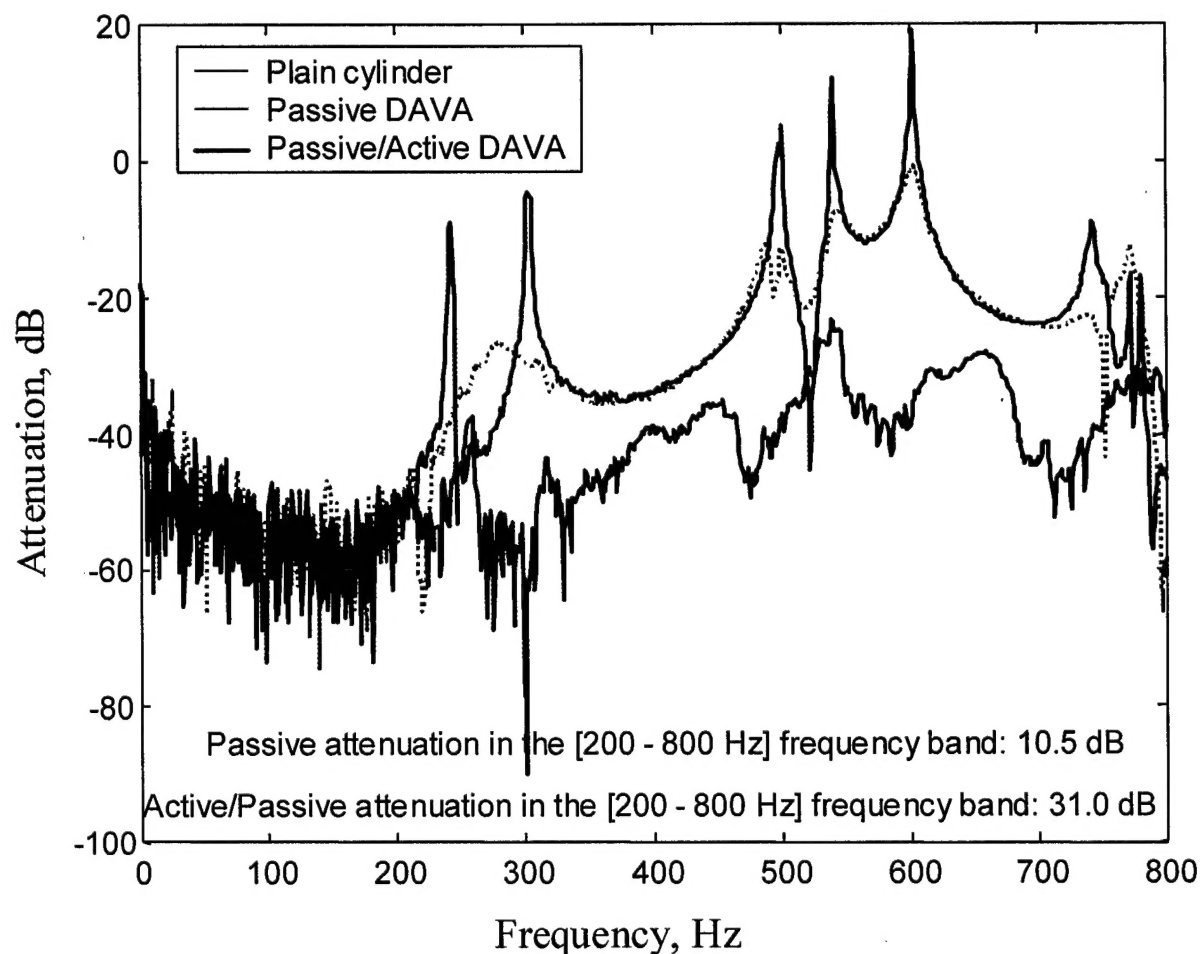


Figure 5. Experimental results on torpedo like cylinder in air

The work performed in the last year of the project thus confirms the very high potential of the DAVA's in providing high global vibration and sound attenuation in a lightweight, conformal, cost effective treatment. Further experiments using DAVA's are summarized in Ref. 2. Future work will concentrate on developing MDOF DAVA's with improved control authority as well as applying the DAVA's to real AF payload fairings and Navy torpedo structures. Investigations will also be carried out to fully understand and optimally utilize the "squeeze" damping mechanism.

## Research on a hierarchical BIO controller

Contemporary control methods such as MIMO feedforward and state space feedback methods are limited to a low number of control channels that can be implemented (approx: 50 by 50). This constraint has correspondingly limited the realization of true smart structures where for micro transducers the control channel count might be of the order of thousands or even greater. Work in the last year has also been directed in developing and implementing effective and efficient control approaches to overcome this limitation. Figure 6 shows a schematic of a biologically inspired hierarchical controller (BIO) developed at VAL-Virginia Tech. In this arrangement there are multiple simple local analog loops whose control parameters are adjusted by an upper level global digital controller. Various control laws can be chosen for the local and upper level controllers depending upon the application. By such an arrangement the local loops are easily expandable to high count systems. The form of the BIO controller in Figure 6 consists of local loops consisting of analog velocity feedback with variable gains. The feedback gains are globally adjusted by a digital controller to minimize a global cost function derived from an array of error sensors. An analysis of the characteristics and performance of the controller has been carried out and is summarized in Ref. 3.

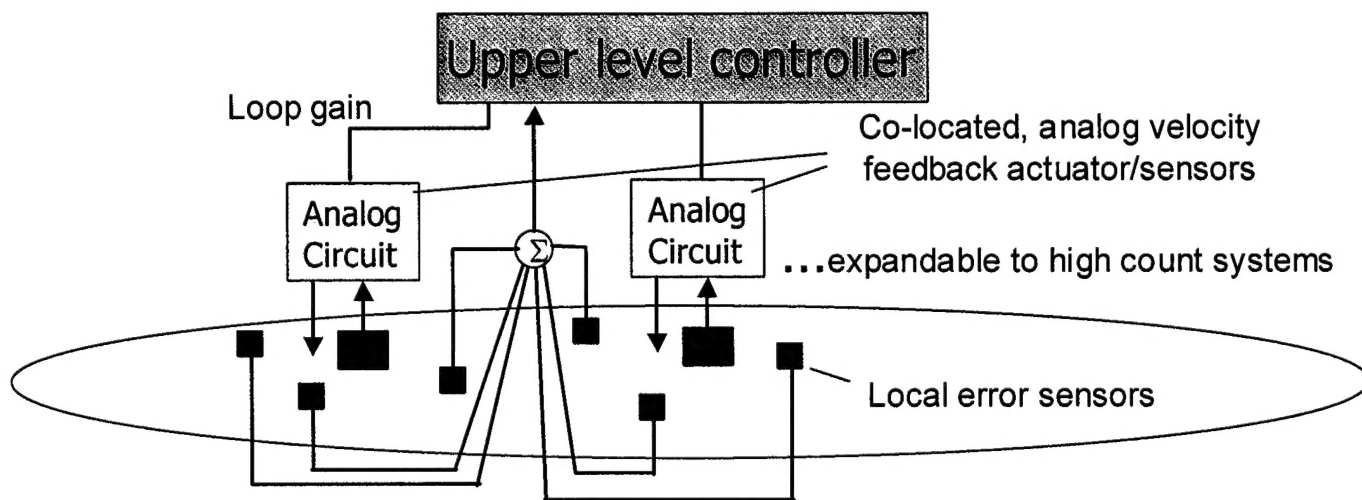


Figure 6. BIO controller schematic

A practical implementation of the BIO controller is shown in Figure 7. The left figure shows DAVA's used as actuators on a Cessna 152 fuselage. Feedback information is taken from two accelerometers located under each DAVA (two were used in this test) while error information is taken from six accelerometers located over nearby panels on the fuselage. The fuselage was excited with a shaker driven by a broadband signal of 0 to 3000Hz. The right hand photo of Figure 7 shows the analog variable gain circuits used as the local controllers. The gains are adjusted by the top level digital controller.

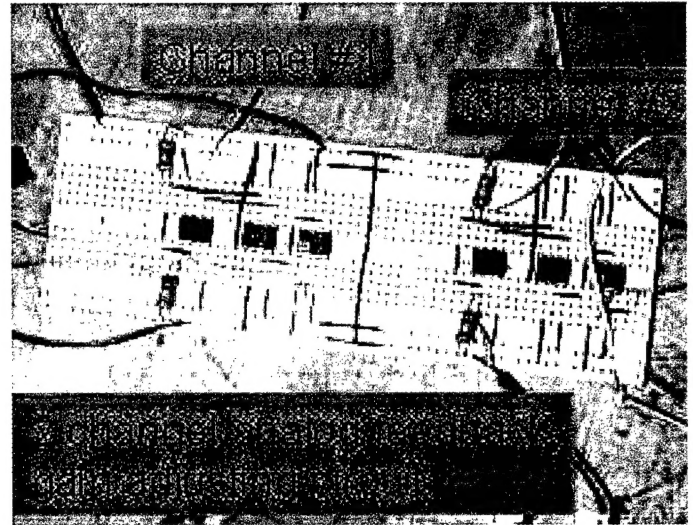
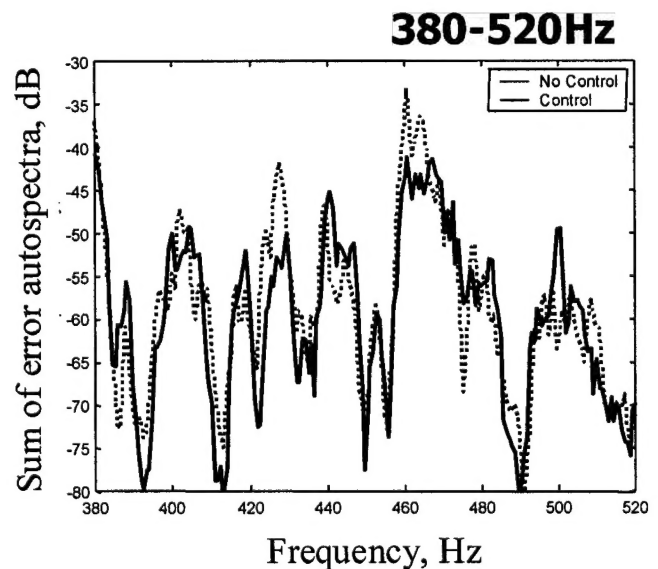
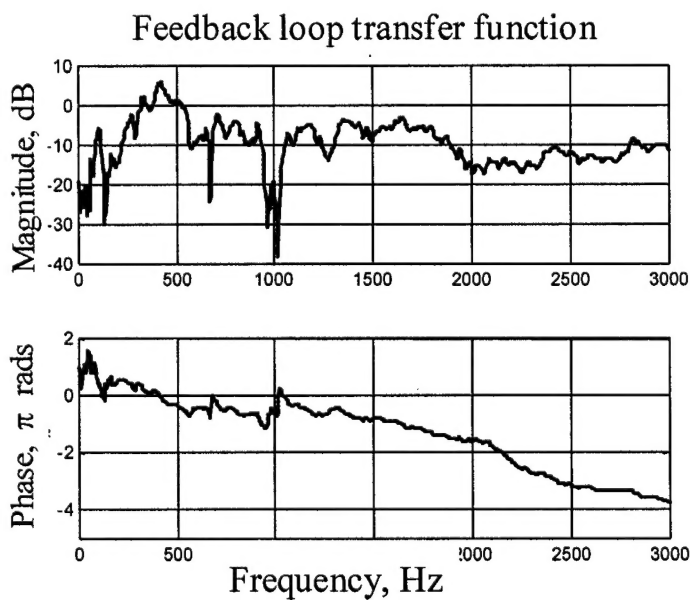


Figure 7. Experimental implementation of the BIO controller

Figure 8 shows example results for a controller designed to reduce fuselage vibrations in the 350 to 550Hz bandwidth. The left figures show the open loop transfer function and the phase indicates instability above 600Hz. However the output of the DAVA's also roll off above 500Hz and this limits the possibility of instability. The right plot of Figure 8 shows that the BIO controller results in 12dB global reductions at the response peaks and 2dB over the control bandwidth. These experimental results are preliminary and better performance is expected with improved control designs guided by the analytical control model.



**2dB reduction  
over bandwidth**

**12dB reduction  
at peak**

Figure 8. BIO controller performance on a Cessna 152 fuselage



Future work will concentrate on further experiments with an expanded control channel count, the implementation of an acoustic cost function and the development of frequency band limited shaped sensors to improve stability.

### **Main Project Conclusions**

1. The work has demonstrated the high potential for low weight, conformal, passive global control of low frequency vibration and associated sound radiation from marine torpedo like structures and others.
2. The work has demonstrated the high potential for low weight, conformal, active global control of low to mid frequency vibration and associated sound radiation from marine torpedo like structures and others.
3. The work has developed viable prototype configurations of DAVA's for practical use.
4. The work has investigated and understood the physical behavior of DAVA's. This knowledge has been used as a design basis.
5. The work has demonstrated the potential of a new hierarchical BIO active control paradigm suitable for very high sensor/actuator count systems.
6. The work has developed and demonstrated a hybrid analog-digital version of the BIO active control system.

### **References**

1. Marcotte, P. and Fuller, C. R., "An analytical model of a Distributed Active Vibration Absorber (DAVA) Applied To A plate With Arbitrary Boundary Conditions," 8<sup>th</sup> Conference on Nonlinear Vibrations, Stability and Dynamics of Structures, Blacksburg, VA, July 23-27, 2000.
2. Marcotte, P., Fuller, C. R. and Cambou, P., "Control of the Noise Radiated by a Plate Using a Distributed Active Vibration Absorber (DAVA)," *Proceedings of ACTIVE-99*, pp. 447-456, Fort Lauderdale, FL, December 2-4, 1999.
3. Kidner, M. and Fuller, C. R., "Control of Large Distributed Structures with Numerous Actuators and A Biologically Inspired Control Architecture," 8<sup>th</sup> Conference on Nonlinear Vibrations, Stability and Dynamics of Structures, Blacksburg, VA, July 23-27, 2000.

## Project Technology Transfer

We have made technology transfers in two main areas in the last year of work. We have been working with Boeing Space and Communications in Huntington Beach, CA (POC: Dr. Haisam Osman) in applying DAVA's to the reduction of launch vehicle payload interior noise. We recently performed experiments at Boeing S&C on DAVA's applied to real payload fairings and successfully demonstrated the potential of the technology for use in realistic launch situations. We have recently begun a cooperative program with Northrop Grumman (POC: Mr. Randy Smith) in which we intend to apply DAVA's to realistic torpedo structures to control radiated sound. We have also been working with Ashai Co. in Japan to apply DAVA's to increase the sound transmission loss of lightweight blown concrete panels for houses. Initial tests on real structures supplied by Ashai have successfully demonstrated the technology.

Future work will extend upon these areas. In cooperation with Boeing S&C we intend to apply DAVA's to an actual payload fairing in use. In cooperation with Northrop Grumman we intend to demonstrate reduction of radiated noise from real torpedoes using DAVA's.

## ONR Database Statistics

3	Papers Published in Refereed Journals Citing ONR Support	0	Papers in Press in Refereed Journals Citing ONR Support
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0	Patents Granted Citing ONR Support	1	Patents Pending Citing ONR Support
4	Presentations	0	Degrees Granted
0	PICOPI	1	Grad Student
0	Post Docs		

## Resultant Refereed Journal Articles

1. Tu, Y. and Fuller, C. R., "Multiple Reference Feedforward Active Noise Control, Part I: Analysis and Simulation of Behavior," Journal of Sound Vibration, 233(5), pp. 745-759, June 22, 2000.
2. Tu, Y. and Fuller, C. R., "Multiple Reference Feedforward Active Noise Control, Part II: Reference Processing and Experimental Results," Journal of Sound Vibration, 233(5), pp. 761-774, June 22, 2000.
3. Johnson, B. D. and Fuller, C. R., "Broadband Control of Plate Radiation Using a Piezoelectric Double-Amplifier Active Skin and Structural Acoustic Sensing," Journal of the Acoustical Society of America, 107(2), pp. 876-884, February, 2000.

## **Resultant Books and Chapters**

1. Fuller, C. R., "Smart Skins for Sound Control," to be published in The Encyclopedia of Smart Materials, John Wyle, New York.
2. Fuller, C.R. "Feedforward Active Control of Vibration," to be published in The Encyclopedia of Vibrations, Academic Press, London.

## **Resultant Presentations**

1. Marcotte, P., Fuller, C. R. and Cambou, P., "Control of the Noise Radiated by a Plate Using a Distributed Active Vibration Absorber (DAVA)," *Proceedings of ACTIVE-99*, pp. 447-456, Fort Lauderdale, FL, December 2-4, 1999.
2. Kidner, M. and Fuller, C. R., "Control of Large Distributed Structures with Numerous Actuators and A Biologically Inspired Control Architecture," 8<sup>th</sup> Conference on Nonlinear Vibrations, Stability and Dynamics of Structures, Blacksburg, VA, July 23-27, 2000.
3. Marcotte, P. and Fuller, C. R., "'An analytical model of a Distributed Active Vibration Absorber (DAVA) Applied To A plate With Arbitrary Boundary Conditions'," 8<sup>th</sup> Conference on Nonlinear Vibrations, Stability and Dynamics of Structures, Blacksburg, VA, July 23-27, 2000.
4. Fuller, C. R. "Distributed Active Vibration Absorber (DAVA) and Associated Control Approaches for Active-Passive Reduction of Sound and Vibration," presented at DARPA TIM, Baltimore, MD, June 27, 2000.

## **Resultant Honors/Awards/Prizes**

C. R. Fuller, "Dean's Award for Excellence in Research," Virginia Tech, April, 2000.